← COVID-19 transmission patterns only seem explainable by aerosols

COVID-19 transmission patterns only seem explainable by aerosols

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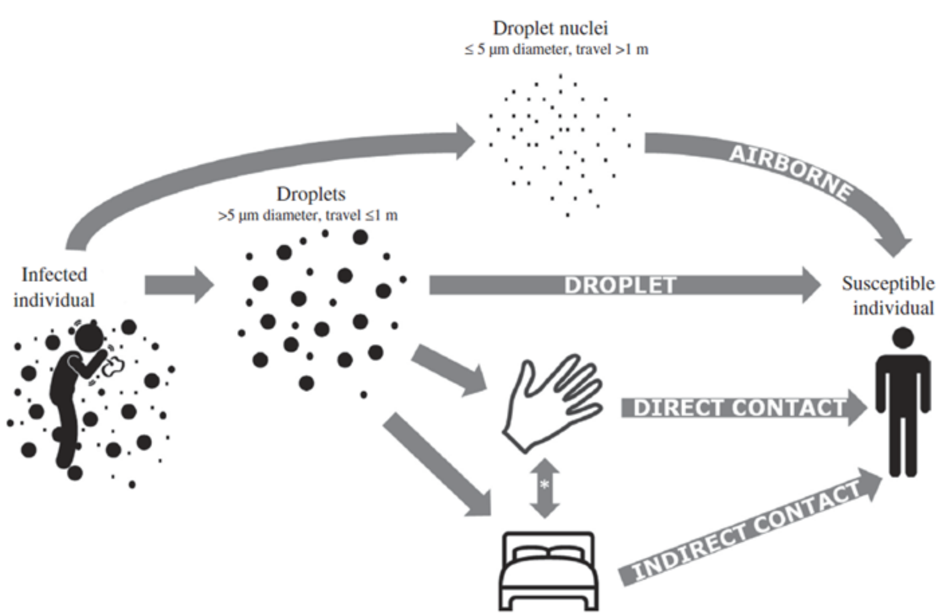
Version: 1.5; 28-Jul-2020 (I started writing this for Twitter but then decided it'd be too painful to enter and read in that format. The writing is still abbreviated. This seems too important to make it pretty and delay publication. I will add on to this later in response to comments, as needed. Although I think some people knew this already, I have not seen an analysis like this before, let me know if you know of one. Understood that it is "big picture", but I am just trying to get the ideas across, since there are huge misunderstandings and errors of interpretation that are the basis of the official guidance).

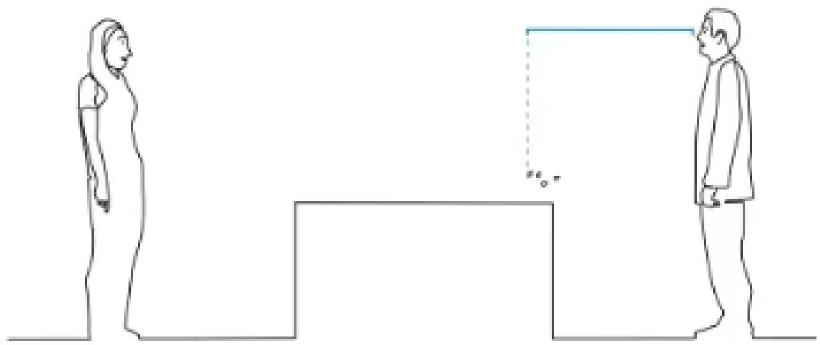
Some additional thoughts on the modes of transmission, which are firming up my confidence on the importance of aerosols. Again hoping for discussion, counter-arguments, other evidence etc. I recommend reading the 11-July-20 Twitter thread first, if you haven't done so. In terms of why arguments against aerosol transmission are weak, read the MedScape Perspective (which is a more complete and readable version of the 16-Jul-20 JAMA thread).



* Transmission routes involving a combination of hand & surface = indirect contact.

discussed fomites as unlikely to be major, and no major arguments emerged against that (though it is possible, so keep washing your hands). Also a UK SAGE member stated in the discussion that the pattern of infections does not seem to match fomites as being major.

So I'll focus on aerosol vs ballistic drops (WHO's "droplets", image below). Don Milton has published an excellent short paper recently reviewing the terminology.



These droplets are too heavy to travel far in the air –
they only travel approximately one metre and quickly settle on surfaces.

Aerosols float in the air from tens of seconds to hours, depending on aerosol size and air flows. Ballistic drops fall to the ground in 1-2 m, in a few sec.

One key piece of experimental evidence is the patterns of transmission, so let's explore whether drops or aerosols are consistent with those. We know that:

(a) Transmission is far more likely indoors than outdoors
(b) A lot of the transmission happens in super-spreader events
(c) Many cases from contract tracing are consistent with "close contact"
(d) Taller people are more likely to contract COVID-19
(e) No long range aerosol transmission has been reported
(r) Transmission patterns in hospitals are not consistent with measles-type disease
(g) Average R0 is ~2-3 with a lot of dispersion (many low values and a few high values)

(If I have missed an important pattern, pls email me with the details and refs.)

Let's discuss them one by one:

(a) Transmission is far more likely indoors than outdoors.

A lot of transmission happens in extended close contact (ECC). There is ECC both indoors & outdoors. Drops are ballistic, there is no time for dilution or UV to remove the virus, they are little affected by indoors or outdoors, their infectivity should be similar in both cases. Aerosols are carried by the wind, there is

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rate. Now move the exact same choir outdoors ("outdoors" sheet), infection drops from 83% to 0.4%.

In the real-world: "The vast majority of transmission seems to be through close contact with an infected individual, primarily in an indoor setting." Or there has been a lack of spikes associated with the Black Lives Matter demonstrations in the US. Only aerosols can explain this.

(b) A lot of the transmission happens in super-spreader events.

Key events can ONLY be explained with aerosols. “Extended close contact” is needed for transmission, per CDC: “within 6 feet of an infected person for at least 15 minutes.” For the Skagit Choir case that we studied, 53 people out of 60 present were infected from the index case in 2.5 h singing. They were aware of COVID-19 and hand-washing recommendations, didn’t shake hands, use hand sanitizer, limited opportunities for fomites (plus fomites unlikely to be major per CDC, see above). Most of the time they were singing in fixed positions, there was nobody within the 2 m landing zone of index patient, they took a couple of 10 min breaks. It is physically impossible for the index patient to have extended close contact with so many people and have enough drops land on them during the breaks. Assuming the index patient was talking to 2 people at a time, that person would have needed 6.6 hrs of break time to have 15 min with each pair to infect 53 people. Privacy limits the release of some info that makes drops even more unlikely, but we can share that info with WHO or CDC. Maybe a few infections could be due to fomite or drops, but the overwhelming majority had to be aerosols. I suspected aerosols when I started working on COVID-19, but I wasn’t sure. The choir case convinced me that it can definitely be transmitted by aerosols, at least in some cases. Similar for other well-studied cases by Yuguo Li, Guangzhou restaurant, buses etc. Or this nursing home in Canada where the ventilation system failed, and every single one of the 226 residents was infected (I am not aware of a published investigation on it). “Contortionist thinking” (B. Nazaroff) is required to explain these w/o aerosols.

(c) many cases from contract tracing are consistent with “close contact”

(c1) The close contact situation

Now we get to the critical point of this thread. Often we hear: “a lot of transmission happens during close contact, which is explained best by drops.” But the logic is flawed, and repetition doesn’t make it correct. Both aerosols and drops are coming out of the mouth and nose of the infected person. Drops can be found ONLY close in front of the infected person. But aerosols are also most concentrated there, in the expiratory plume in front of infected person, and are diluted quickly with distance, given typical indoor wind speeds of 5 cm/s plus some momentum from the exhaled flow. A susceptible person will breathe the highest aerosol dose under close contact, much higher than if the air is diluted onto the entire room. A person breathing out smoke aerosols visualizes this plume. The graph below (Nielsen & Liu, 2020) illustrates the transition from the

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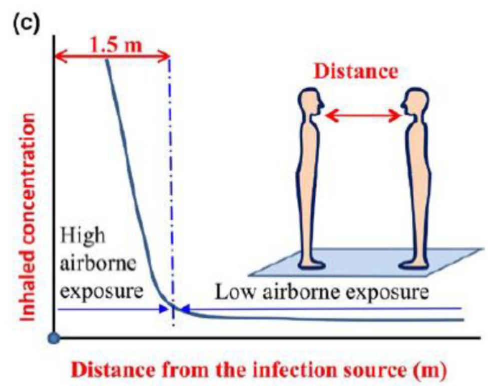

Exposure from droplet nuclei (aerosols)
in rooms with sufficient ventilation

Detailed physics-based modeling by Yuguo Li, using measured amounts and size distributions of expired particles and very well-established physics, shows that the exposure at close contact when talking is dominated by aerosols. I use talking and not coughing because it is the most relevant for a/presymptomatic transmission in the community. Drops are only competitive at less than 20 cm distance. Typical US conversation happens at 45-90 cm. At 50 cm distance, aerosol exposure is x100 more important. At 1 m distance, aerosols are over x2000 more important. This figure shows the exposure to drops (red) and aerosols (black) as a function of distance from the speaker. Note the logarithmic Y scale.

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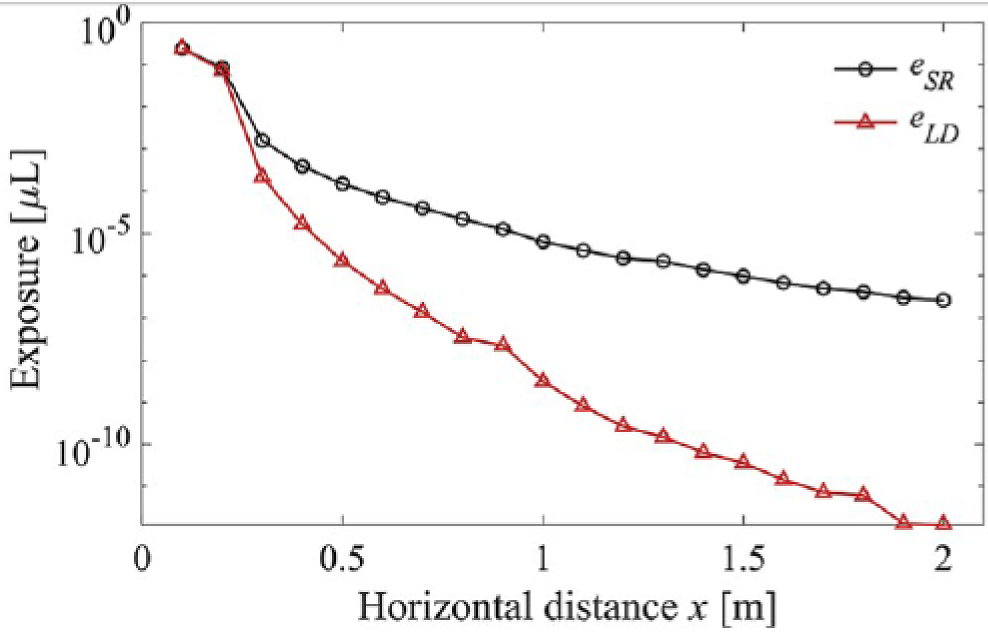

This is solid work with realistic assumptions. There are uncertainties, but not the x100-2000 that would be needed to make drops competitive.

Influenza virus has been shown to be most concentrated in smaller particles (Yan et al., 2018), which would favor the aerosol route even more. This is thought to be due to the bubble bursting-like mechanism of respiratory particle formation, similar to what is observed for the ocean surface (e.g. Kim Prather's work).

So if close contact dominates, aerosols likely dominate! Being generous by a factor of 100-2000, aerosols are still competitive with drops. But definitely **aerosols cannot be discarded as negligible based on the fact that many infections happen at close contact.**

(c2) Consistency with the room scale transmission

Now we transition to the room scale. The expired flow is eventually mixed into the room by air currents, depending on ventilation and thermal gradients. This leads to a lot of dilution. An example is smoke diluting into a room, as in the picture below. So for a virus that is infective through aerosols, but much much less than measles, it is a challenge to build up a concentration in the room which is comparable to the concentration in the breathing area of the close contact situation. But is it possible, and is it consistent with the data?

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How much larger is the dilution of aerosols, compared to the close contact situation?

Let's do a simple order-of-magnitude estimate comparison of the dilution in the close contact situation (that we know leads to infection w/ people talking) and the room situation (that we know led to widespread infection for the choir). The schematic below from Yuguo Li's paper gives us an idea of the dimensions.

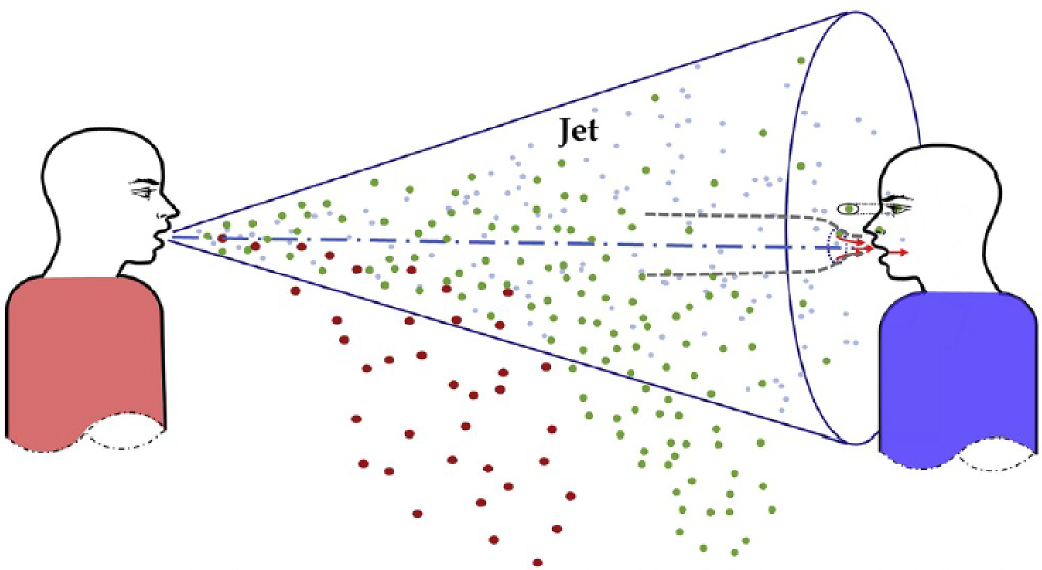

Fig. 1. Schematic diagram of close contact scenario with exhalation from the infected (left) and inhalation through the mouth of the susceptible person (right).

Let's assume that the expiratory flow (0.6 m3 / h when talking) is diluted into an approx. 35 cm diameter cylinder that contains most of the exhaled breath. Assuming an indoor air speed of 0.1 m/s and a distance of 1 m, the exhaled air will spend ~10 seconds in that volume. So that's a dilution rate of ~60. We know

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min. of close contact, and that volume is 59 parts "clean air" and 1 part exhaled air from the infected person. So then we can estimate the infectious dose as inhaling 2.5 liters of undiluted exhaled breath from the infected person.

Now let's do the same calculation for the Skagit choir. Assuming an 800 m3 room, 1.5 h duration (less than the actual duration, to approximately account for some limited ventilation and the buildup over time), and an exhaled flow of 1.1 m3/h during singing. So the dilution factor of the expired air from the index case is ~480. Importantly, respiratory particles increase x6 when singing (see line 66 "readme" of http://tinyurl.com/covid-estimator and references therein). So the concentration of respiratory particles in the room was equivalent to a dilution factor of 80 in the close contact situation, very similar to 60 above, given the approximations. But what matters for infection is the amount of resp. particles breathed in, and for that we need to factor in the exposure time, which is a factor of 6 longer than a 15 min close contact. So the amount of respiratory particles (from the index case) breathed in for the susceptible members of the choir was actually ~4 times higher than for the typical close contact, which we know often leads to infection. No surprise that it led to so many infections!

Within these approximations, the results are very consistent. Hence we now understand that many infections happen at close range, which is expected since the concentrations of respiratory aerosols are most concentrated there. To have room-level infection, we need to help the virus build up enough concentration to infect (aided by low ventilation, no masks, talking or singing), and have enough time to breath in those particles (long duration). Crowding also helps because it increases the probability that an infected person happens to be present, and also increases the number of infected people that can result.

Therefore we can consistently explain BOTH close contact and room-level transmission with aerosols. And we can't with drops. And importantly, since cases like the choir are almost certainly due to aerosols, then a logical consequence is that close contact has to be infective through aerosols. It is not possible for close contact to not be quite infective through aerosols, if those same aerosols can infect when diluted to the room scale.

COVID-19 is (at least for most people) not super-contagious by aerosols, nowhere near measles. It is not "airborne" in the medical use of that term, it is "opportunistic airborne." The exhaled aerosols are enough to infect when they are more concentrated with limited dilution, i.e. in a close contact situation. But when diluted into a room, if there is good ventilation, masks, not talking, HVAC or portable-HEPA filtering, it can't build enough concentration in the room to infect. Or the dose is limited if we keep the time short. But when given the opportunity (combo of those factors missing, as for the as choir), then it can infect.

(d) No long range aerosol transmission has been reported

Here we call "long range aerosol transmission" the transmission to people who are in different rooms than the infected person, at distances significantly larger than the room-scale outbreaks (choir, restaurant etc.).

rooms and some outside air, and is greatly diluted. There will also be some particle losses to the ducting walls and heat exchangers (we know because virus RNA has been found inside HVAC units -- but don't panic, keep reading), and maybe filtering. The virus just doesn't have a chance to build up to an infective concentration due to the high dilution. It is possible that some cases happen under favorable circumstances, but it should be a very small fraction of the cases, and they will be hard to identify. During SARS, aerosol transmission was the most likely explanation for the Amoy Gardens outbreak, and five similar cases have been reported for COVID-19. However, those may involve fecal aerosols and not respiratory ones.

Measles transmits through aerosols as well, but it is typically much more infective, either because more viruses are exhaled, or because less inhaled viruses are needed for infection than for COVID-19 (I am told it is not known which of these is more important). From comparison of outbreaks, it seems that measles is x10-100 more infective than COVID-19, per unit exhaled breath (see readme of my estimator). So of course it can overcome a lot more dilution and infect at long range.

(e) Transmission patterns in ICUs are not consistent with measles-type disease

Outside of aerosol-generating procedures, and under a well ventilated situation, let's say 6 air exchanges per hour as in many hospitals (current US regulation is 12 ACH, but some hospitals are older), the equivalent room-level dilution factor is ~685. Now add well-worn surgical masks that filter 80% of the aerosols, and the equivalent dilution factor is 3400. The concentration of viable virus in the respiratory tract is also low for people in advanced stages of the disease, so the emission rate will likely be much lower than for an infected person just before the onset of symptoms. No surprise that infection is often not rampant in ICUs. But the same aerosol mechanism that is often limited in hospitals is likely playing a major role in the community.

(f) R0 is ~2-3 with a lot of dispersion (many low values and a few high values)

Here we refer to the average R0 across large regions. R0 for an individual outbreak can be very large (e.g. R0 = 53 for the choir case).

Now it is also clear why R0 has that pattern. The virus is much less contagious than measles. It typically needs close contact, which limits the number of infections per person. But under the right circumstances indoors, it can build up to high enough concentrations at the room level and lead to super-spread. This explains the high dispersion. Drops would need a very high variability in the number of close contact encounters per person.

So let's summarize all the characteristics

	Aerosols explain it?	Drops explain it?
a) Outdoors << indoors	Yes	No
b) Super-spreading events	Yes	No

and room-scale transmission		
d) No obvious long range transmission	Yes	Yes
e) Low transmission in hospitals	Yes	Yes
f) Low R0 w/ high dispersion	Yes	Yes R0 No dispersion

Conclusions

COVID-19 most likely has a major (most likely dominant) aerosol contribution. Understanding this allows for smarter control and re-opening of societies. **The social distancing recommended by WHO works, but it works mostly for a different reason than the one used to justify it. It is likely reducing aerosol exposure, not getting you away from the ballistic drops.** Masks, avoiding indoor crowded locations, and keeping the time indoors short work because they reduce aerosol exposure. We are recommending these things already. But people are confused e.g. about masks because many don't understand why they need to wear them, once they are socially distanced. In addition, understanding the aerosol mechanism makes obvious the critical value of additional things we can do, in particular increasing ventilation (opening windows, increasing outdoor air in HVAC systems etc.) and filtration (e.g. portable HEPA filters, or in HVAC systems) for indoor spaces.

So that's it. It does seem to me that COVID-19 fits the pattern of a lower-contagiousness aerosol-driven disease. With perhaps some unusual high-contagiousness individuals driving some of the superspreading events. Any input and comments would be appreciated.

Note that per Chen et al. (2020), "Reviewing the literature on large droplet transmission, one can find no direct evidence for large droplets as the route of transmission of any disease."

I realize that this may be shocking to some in medical infectious diseases, who were taught that diseases are either airborne like measles or not significantly airborne (which actually makes no sense when you think about it). But the evidence is stacking up.

Appendix: Transmission vs height

A preprint published on 15-July-2020 (Anand et al., 2020) has reported that taller people are more likely to get COVID-19, which holds especially for UK men (taller than 6 ft) pre-lockdown. I posted this on Twitter on 28-Jul and many experts commented that they thought the result was weak for statistical and study design reasons. Therefore I don't include this as a real pattern of transmission yet. I asked others who have similar databases to look at this effect, hopefully someone will.

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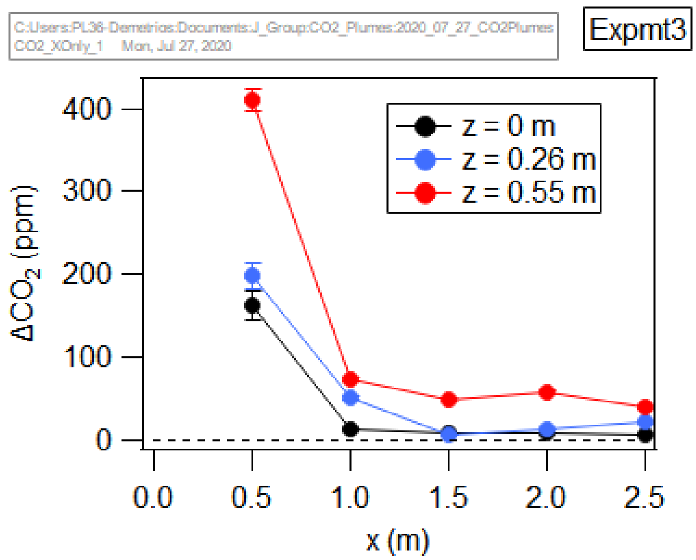
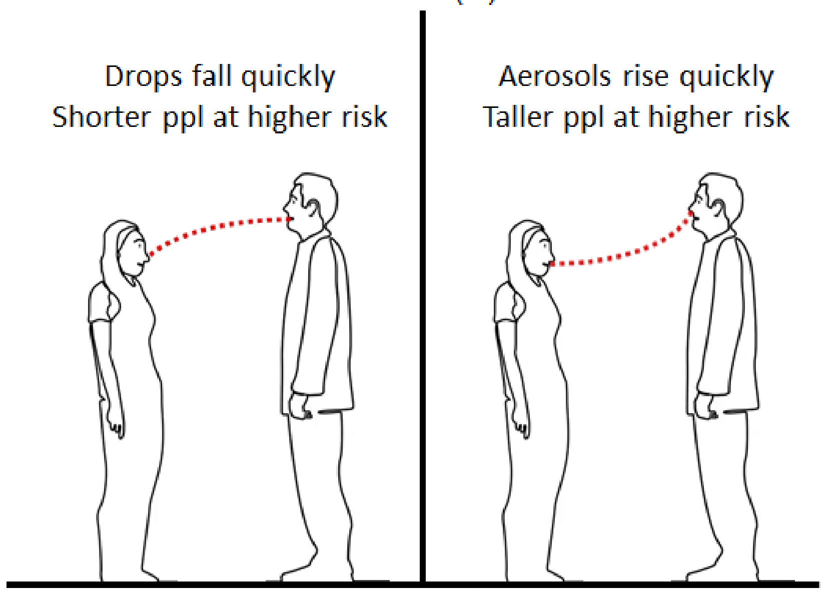
expected to have a higher chance of contagion. On the other hand, expiratory aerosols rise in cooler surroundings, due to buoyancy of the warmer exhaled air. This is discussed by Chen et al. (2020). We have also seen the rise of the exhaled plume in initial experiments trying to characterize the close proximity situation, by measuring CO_2 at different heights in front of a person speaking. The data below, taken by Dr. Demetrios Pagonis in our group, shows the CO_2 concentration while speaking, with CO_2 measured at 3 different heights (z = 0 is mouth height, the other values are higher), and as a function of horizontal distance from the mouth. Indeed the CO_2 enhancement is significantly larger above the mouth height. Small enough aerosols (e.g. 10 um) settle very slowly and will just follow the same dispersion pattern as the CO_2.





The pattern of higher cases for tall men is consistent with aerosol and not droplet transmission, per the schematic above. This is an interesting result. Hopefully it can be explored with other databases to see if the trend also holds in those.

to see the key connections, and to Maurice de Hong for his inspiring post. And thanks to the group of 36 for innumerable discussions about the topic. And also to many other folks throughTwitter, email etc.